Measurement of the η_c Transition Form Factor at BaBar

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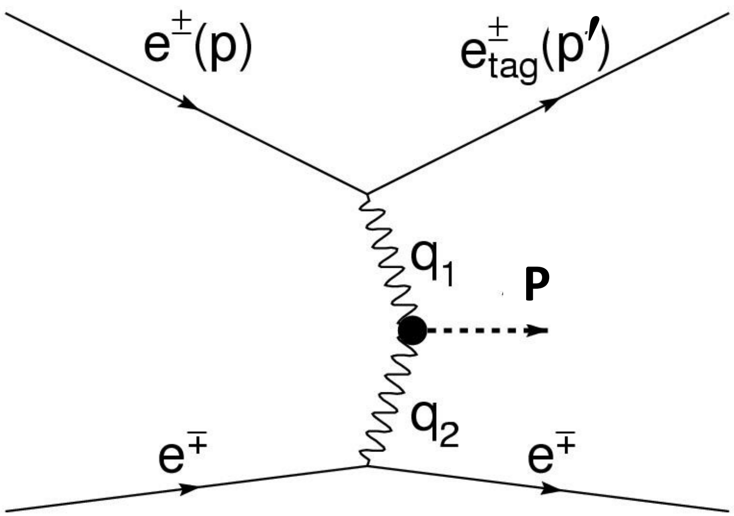
Representing the BaBar Collaboration

Two-Photon Reaction: $e^+ e^- \rightarrow e^+ e^- P$



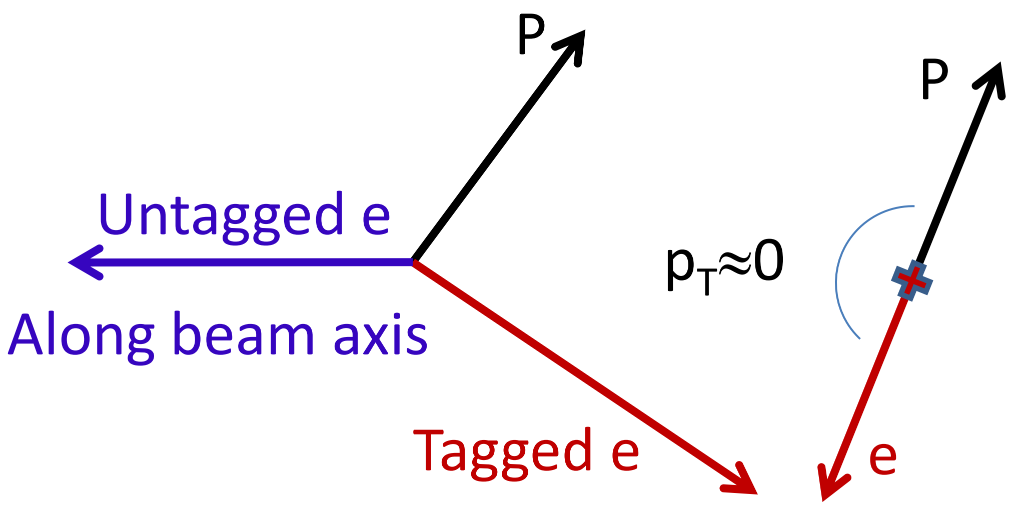
- A photon is emitted from each beam and the two photons collide
- Electrons are scattered predominantly at small angles.
- For pseudoscalar meson production the cross section depends on a form factor $F(q_1^2, q_2^2)$, which describes the $\gamma^*\gamma^* \rightarrow P$ transition.

Brodsky, Kinoshita and Terazawa, PRD 22, 2157 (1980)

Two-Photon Reaction: $e^+ e^- \rightarrow e^+ e^- P$

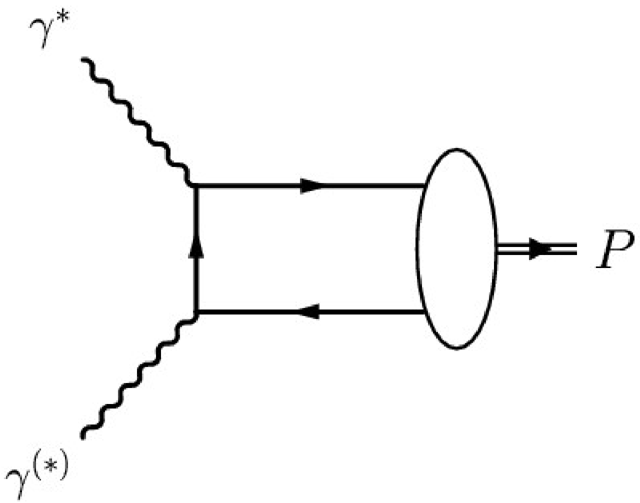
No-tag mode:
- ✓both electrons are undetected
- ✓better statistics than single-tag
- ✓$q_1^2,\ q_2^2 \approx 0$
- ✓$\Gamma_{\gamma\gamma}$ or $F(0,0) \equiv F(0)$

Single-tag mode:
- ✓one of electrons is detected
- ✓$Q^2=-q_1^2=2EE'(1-\cos\theta)$
- ✓$d\sigma/dQ^2 \sim 1/Q^6$ for η_c
- ✓$F(Q^2,0) \equiv F(Q^2)$



- ✓electron is detected and identified
- ✓η_c are detected and fully reconstructed
- ✓electron + meson system has low $p_\perp$
- ✓missing mass in an event is close to zero

Two-Photon Reaction: Single Tag



Single tag form factor depends only on Q^2 of highly virtual photon

$$F(Q^2) = \int T(x,\mu^2)\,\varphi(x,\mu^2)\,dx$$

Hard scattering amplitude for $\gamma^*\gamma \to q\bar{q}$ transition which is calculable in pQCD

Nonperturbative distribution amplitude describing transition $P \to q\bar{q}$

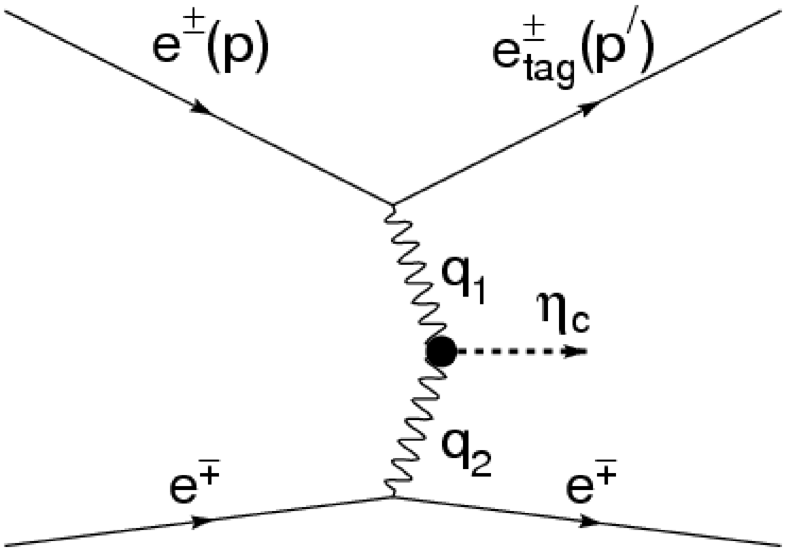
x is the fraction of the meson momentum carried by one of the quarks in the infinite momentum frame

Lepage and Brodsky, PRD 22, 2157 (1980)

η_c Mass and Width

- Measurements of η_c mass and width vary depending on production method
  - Cross section of of $J/\psi \rightarrow \eta_c\gamma$ ($\psi(2S) \rightarrow \eta_c\gamma$) varies according to E_γ^3 (E_γ^7), distorting lineshape
  - Measurement of η_c mass and width in two-photon production does not suffer from this issue
- Measured using higher statistics of no-tag sample

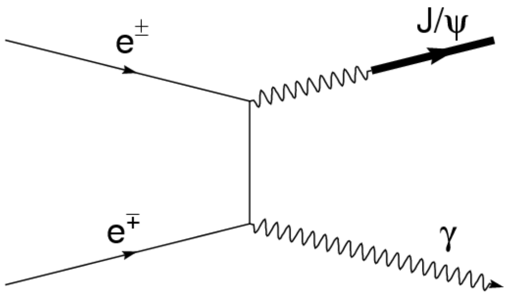
Analysis of $e^+e^- \to e^+e^-\eta_c$



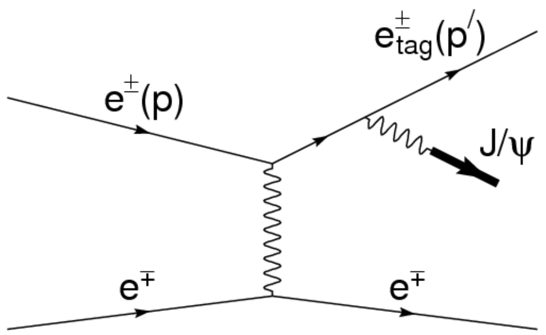
PRD 81, 052010 (2010)

Analysis of $e^+e^- \rightarrow e^+e^-\eta_c$

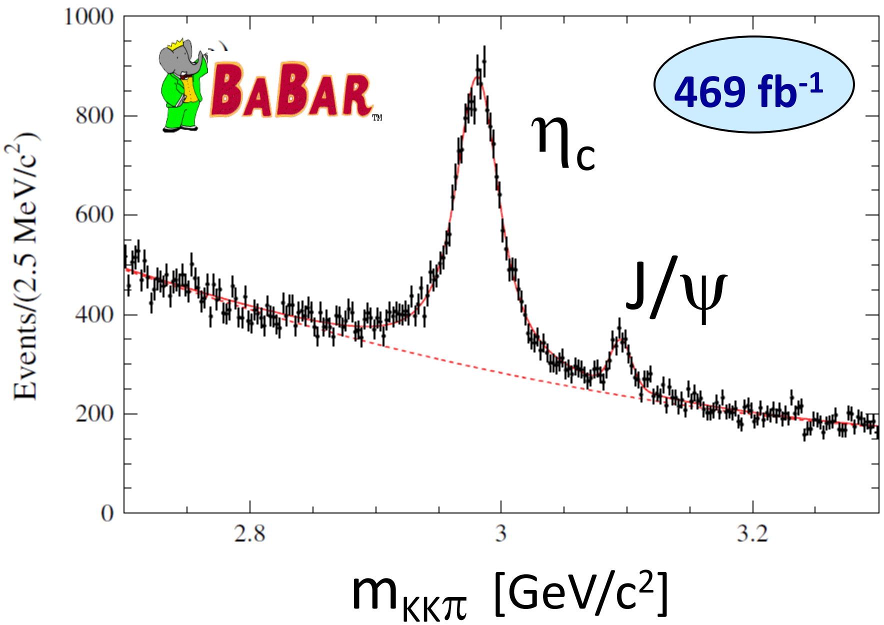
- $e^+e^- \rightarrow e^+e^-\eta_c$ where $\eta_c \rightarrow K_S K^+\pi^-$, $K_S \rightarrow \pi^+\pi^-$
- **No-tag ($Q^2 \approx 0$) mode**
  - extract mass and width
  - used for single-tag form factor normalization
  - background from $e^+e^- \rightarrow J/\psi\,\gamma$, $J/\psi \rightarrow \eta_c\gamma$



- **Single-tag mode**
  - extract form factor
  - background from $e^+e^- \rightarrow e^+e^- J/\psi$, $J/\psi \rightarrow \eta_c\gamma$



$e^+e^- \rightarrow e^+e^-\eta_c$, $\eta_c \rightarrow K_SK^+\pi^-$, No-Tag Mode

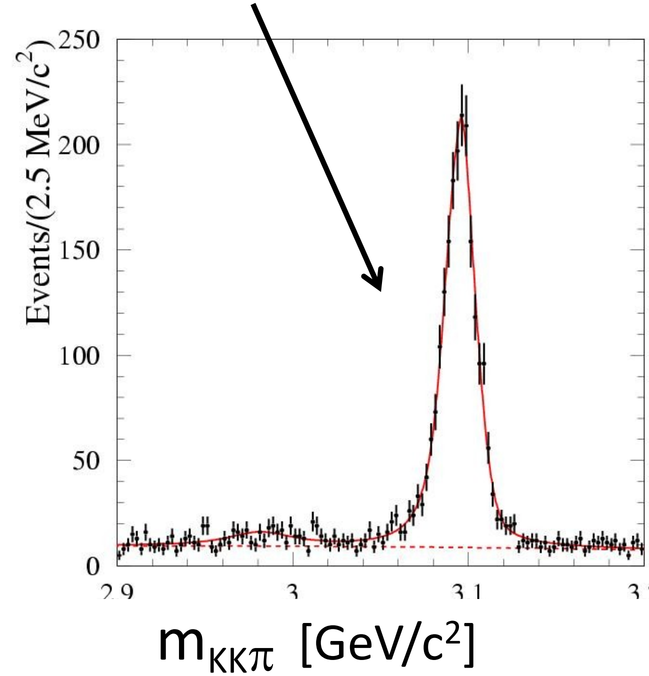


Momentum of η_c candidate in CM frame for η_c produced in ISR:

$$p^* = (\sqrt{s}/2) \times \; (1 - M^2_{K\bar{K}\pi}/s)$$

ISR events can be separated from two-photon events using the kinematic criterion:

$$p^*/(1 - M^2_{KK\pi}/s) > 5.1 \text{ GeV}/c$$



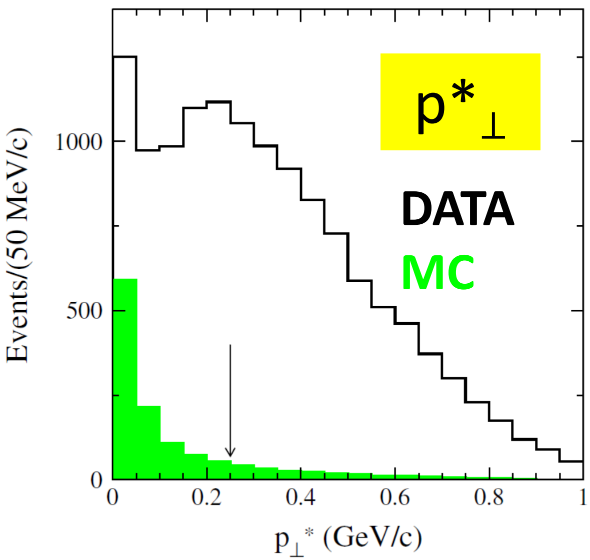
η_c mass	2982.2±0.4±1.6
η_c width	31.7±1.2±0.8
η_c yield	14090 ± 330 ± 480

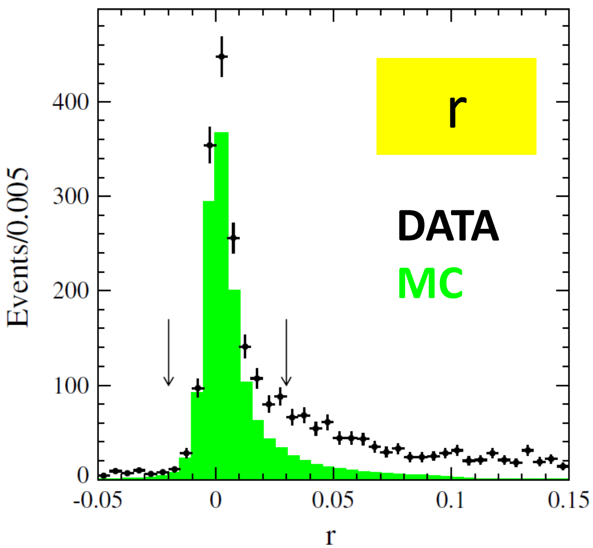
$e^+e^- \to e^+e^-\eta_c$, $\eta_c \to K_S K^+\pi^-$, Selection

- Four (five) charged tracks for no-tag (single-tag), plus a possible beam-generated track
- K_S mass window: 0.4875-0.5075 MeV/c^2
- $|\cos \theta^*_{\eta_c}| > 0.95$ (throughout, * denotes CM frame)
- K_S decay angle $\cos \psi_{K_S} > 0.95$

Additional Selection for Single-tag

- Electron in $0.387 < \theta < 2.400$
- $|\cos \theta^*_{e\eta_c}| > 0.95$
- $p^*_\perp < 0.25$ GeV/c
- $-0.02 < r < 0.03$, where $r = \dfrac{\sqrt{s} - E^*_{e\eta_c} - |p^*_{e\eta_c}|}{\sqrt{s}}$





$e^+e^- \to e^+e^-\eta_c$, $\eta_c \to K_S K^+\pi^-$, No-Tag Mode

- The sources of non-resonant background are two-photon and ISR processes.
- The peaking background is $e^+e^- \to J/\psi\gamma$, $J/\psi \to \eta_c\gamma \to K_S K^+\pi^-\gamma$. It is calculated from the fitted number of $J/\psi \to K_S K^+\pi^-$ events. 4%
- Main sources of systematic uncertainties are unknown background shape and possible interference between η_c and non-resonant two-photon amplitudes.

	Mass, MeV	Width,MeV
PDG	2980.5±1.2	27.4±2.9
BABAR(88 fb^{-1})	2982.5±1.1±0.9	34.3±2.3±0.9
BABAR(469 fb^{-1})	2982.2±0.4±1.6	31.7±1.2±0.8

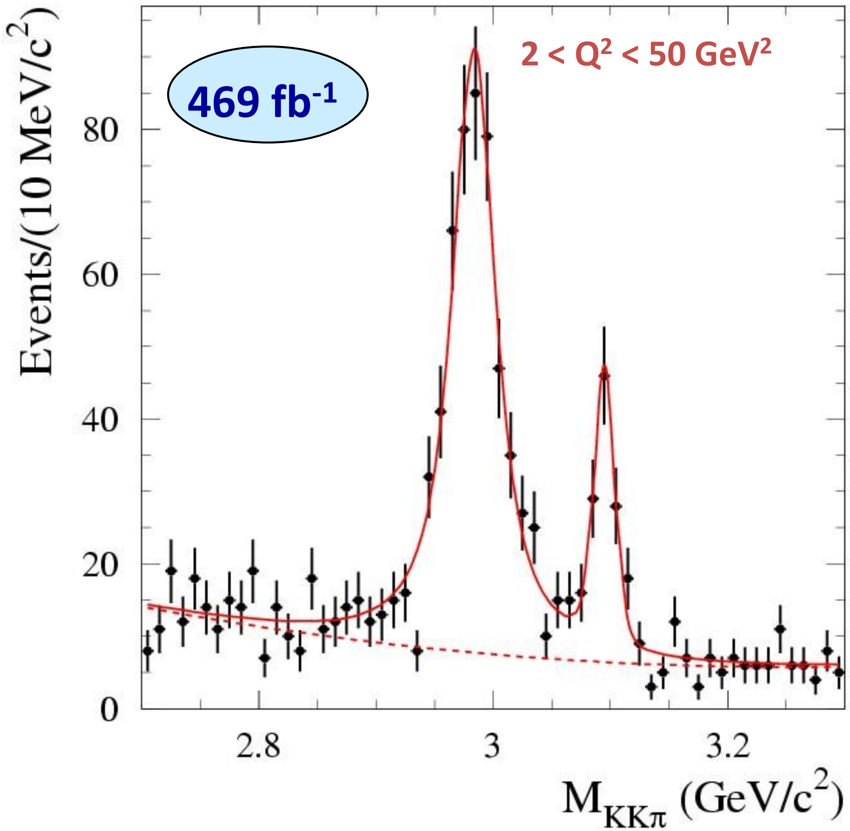
Systematics (η_c lineshape or possible interference with non-resonant amplitudes) neglected in older measurements in PDG average

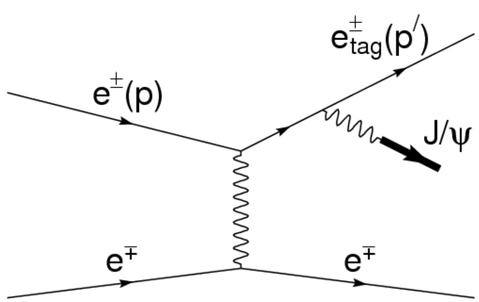
Rate measurement consistent with previous analyses

BABAR : $\Gamma(\eta_c \to \gamma\gamma)B(\eta_c \to K\bar{K}\pi) = 0.374 \pm 0.009 \pm 0.031\,\mathrm{keV}$

PDG: 0.44±0.05 keV CLEO [PRL 92, 142001 (2004)]: 0.407±0.022±0.028 keV

$e^+e^- \to e^+e^-\eta_c$, Single-Tag





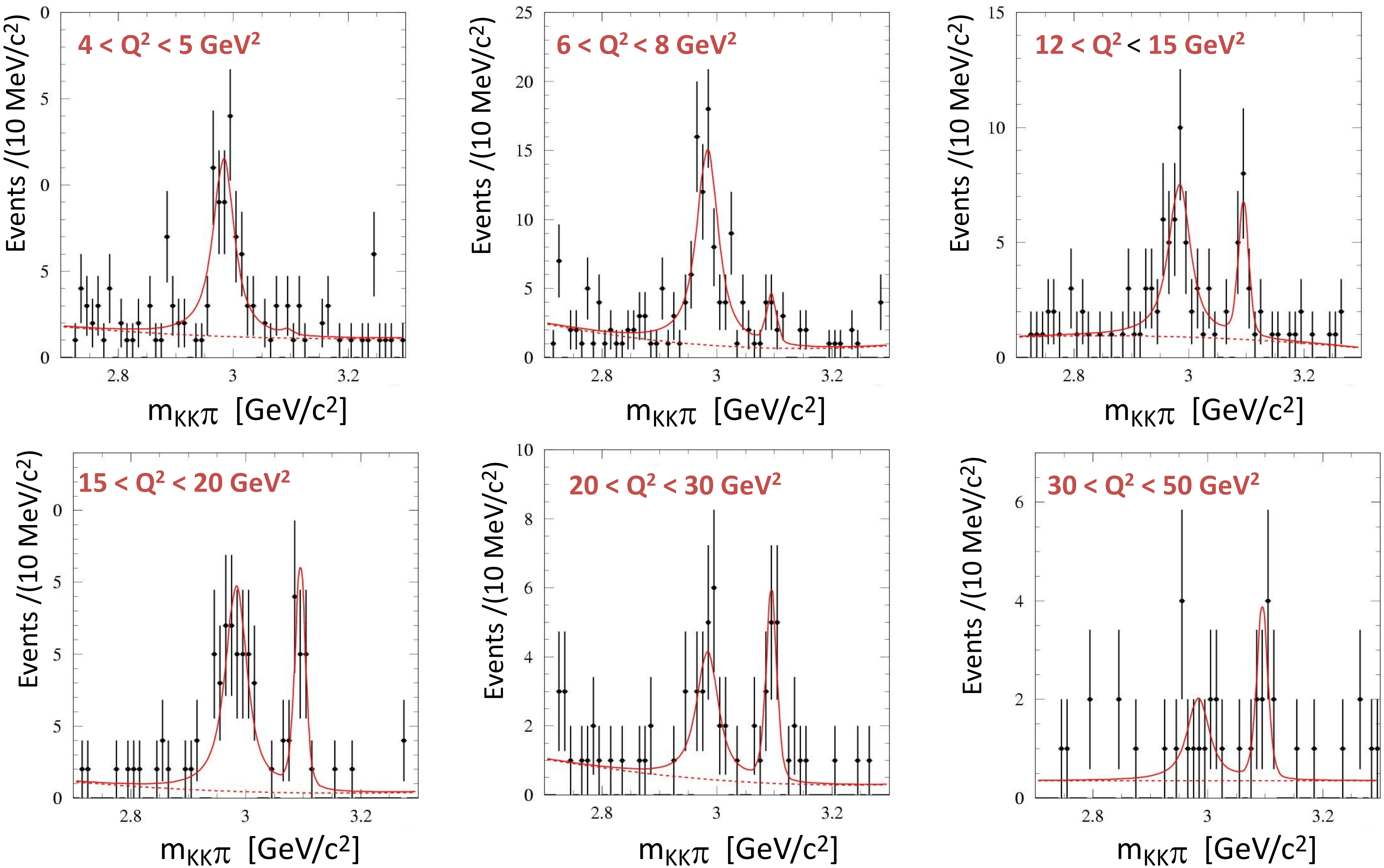
$$m = 2985.7 \pm 2.0\,\mathrm{MeV/c^2}$$
$$\Gamma = 31.9 \pm 4.3\,\mathrm{MeV}$$
$$N = 530 \pm 41 \pm 17$$

Compared to N=8±5 from L3 at LEP

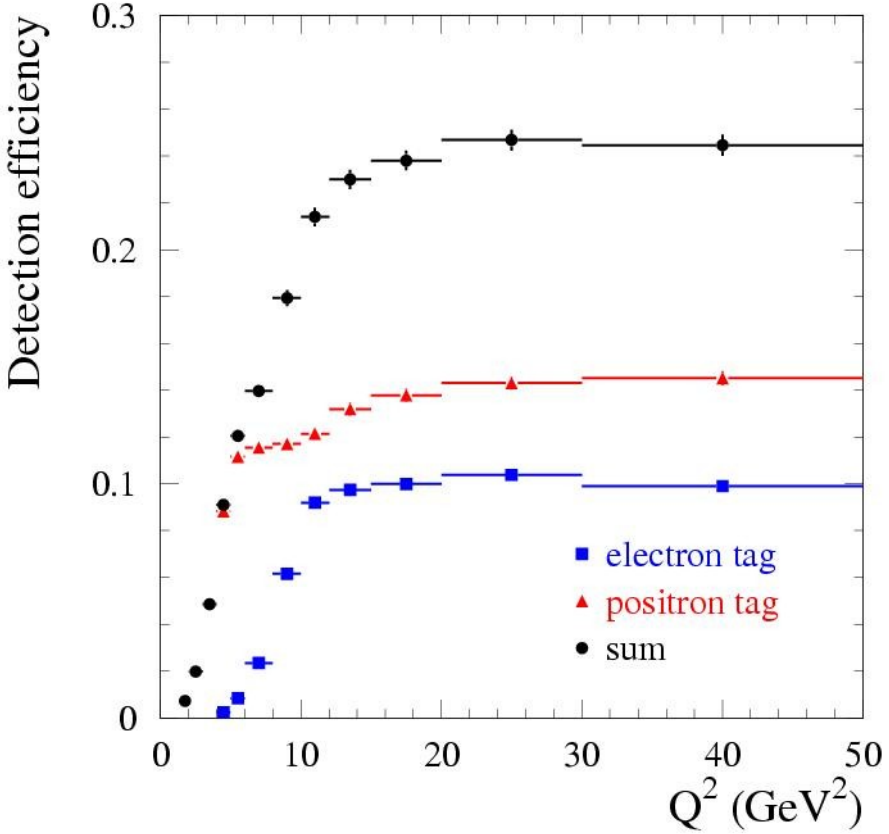
Phys. Lett. B461, 155 (1999)

Peaking background from $e^+e^- \to e^+e^- J/\psi$, $J/\psi \to \eta_c\gamma \to K_S K^+\pi^- \gamma$ is calculated from the fitted number of $J/\psi \to K_S K^+\pi^-$ events. It varies from about 1% at $Q^2<10$ GeV^2 to about 5% at $Q^2 \approx 30$ GeV^2

$e^+e^- \to e^+e^-\eta_c$, Single-Tag Mode



$e^+e^- \to e^+e^-\eta_c$, Detection Efficiency



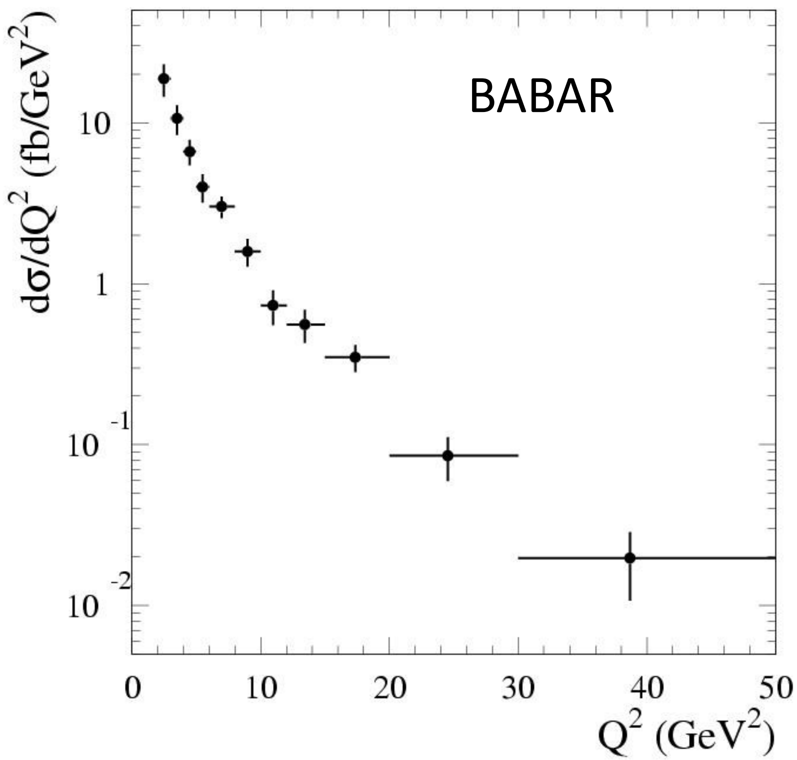
- Due to the energy asymmetry of our e^+e^- collisions, the Q^2 region below 6 GeV^2 is measured with positron tags only.
- We measure the cross section above $Q^2 = 2$ GeV^2 where the efficiency is about 2%.
- For no-tag events, the efficiency is (14.5 ± 0.2)%
- The data Dalitz plot distribution is used to reweight MC events. The shift of efficiency is small, (-1.1 ± 1.6)%.

$e^+e^- \to e^+e^-\eta_c$, Systematic Uncertainty

Source	No tag, %	Single tag, %
trigger, filters	1.2	—
η_c selection	5.9	5.7
track reconstruction	1.4	1.5
$K^{\pm}$ identification	0.4	0.5
$e^{\pm}$ identification	$\cdots$	0.5
total	6.2	5.9

- Trigger/filter systematic estimated using prescaled events that do not pass background filters
- To estimate systematic uncertainties due to selection criteria we vary
  - K_S mass window: 0.4875-0.5075 MeV/c^2 $\Rightarrow$ 0.475-0.52 MeV/c^2
  - Limit on transverse momentum: 0.25 GeV/c $\Rightarrow$ 0.5 GeV/c
  - $0.387 < \theta < 2.4$ for kaon and pions (most significant effect; ~6%)
  - $-0.02 < r < 0.03$ $\Rightarrow$ $-0.02 < r < 0.06$ (r is a restriction on ISR photon energy)
- $K^{\pm}$, $e^{\pm}$ systematics evaluated using data control samples

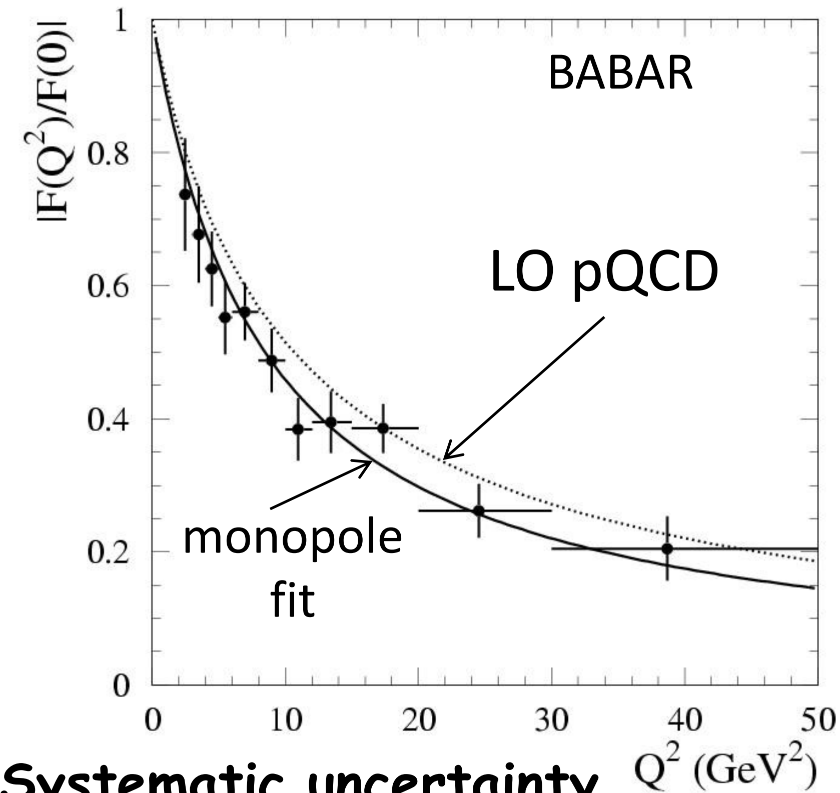
$e^+e^- \to e^+e^-\eta_c$, Cross Section



Systematic uncertainty independent of Q^2 is 6.6%.

• detection efficiency	5.9%
• background subtraction	2.5%
• radiative corrections	1%
• luminosity	1%

$e^+e^- \to e^+e^-\eta_c$, Form Factor



Systematic uncertainty independent of Q^2 is 4.3%.

- **detection efficiency**
- **number of no-tag events**
- **stat. error on no-tag efficiency**
- **background subtraction**
- **radiative correction uncertainty**

✓ The form factor is normalized to F(0) obtained from no-tag data.

✓ We fit the function

$$F(Q^2) = \frac{F(0)}{1 + Q^2/\Lambda}$$

to the form factor data. The result

$$\Lambda = 8.5 \pm 0.6 \pm 0.7 \text{ GeV}^2$$

is consistent with expectations of

$\Lambda = m^2_{J/\psi} = 9.6 \text{ GeV}^2$ (Vector Meson Dominance)

$\Lambda = 8.4 \pm 0.4 \text{ GeV}^2$ (Lattice QCD)

PRL97, 172001 (2006)

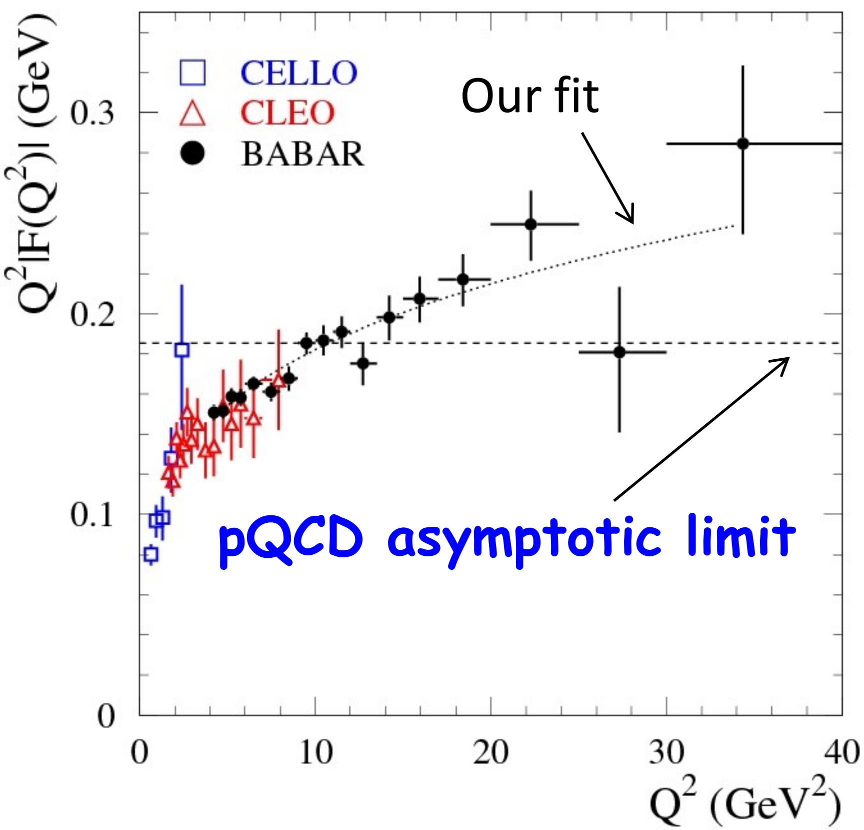
✓ Our data lie systematically below a leading-order pQCD calculation. [T. Feldmann, P.Kroll]

Phys. Lett. B413, 410 (1997)

Summary

- The $\gamma^*\gamma \to \eta_c$ form factor has been measured for the Q^2 range from 2 to 50 GeV^2.
- The form factor data are well described by the monopole form with $\Lambda = 8.6 \pm 0.6 \pm 0.7$ GeV^2. The data are in reasonable agreement with both Vector Meson Dominance model and lattice QCD predictions.
- Precise measurement of η_c mass and and most precise single measurement of η_c width
- Measurement of η_c transition form factor part of a program at BaBar to measure reactions of the form $e^+e^- \to e^+e^- P$

$e^+e^- \to e^+e^-\pi^0$, Form Factor



✓ $4 < Q^2 < 9$ GeV^2: our results are in a reasonable agreement with CLEO data but have significantly better accuracy.

✓ $Q^2 > 10$ GeV^2: the measured form factor exceeds the asymptotic limit $\sqrt{2}f_\pi = 0.185$ GeV. Most models for the pion distribution amplitude give form factors approaching the limit from below.

✓ $4 < Q^2 < 40$ GeV^2: our data are well described by the formula

$$Q^2|F(Q^2)| = A\left(\frac{Q^2}{10\,\mathrm{GeV}^2}\right)^{\beta}$$

where A=0.182±0.002 GeV and β=0.25±0.02.

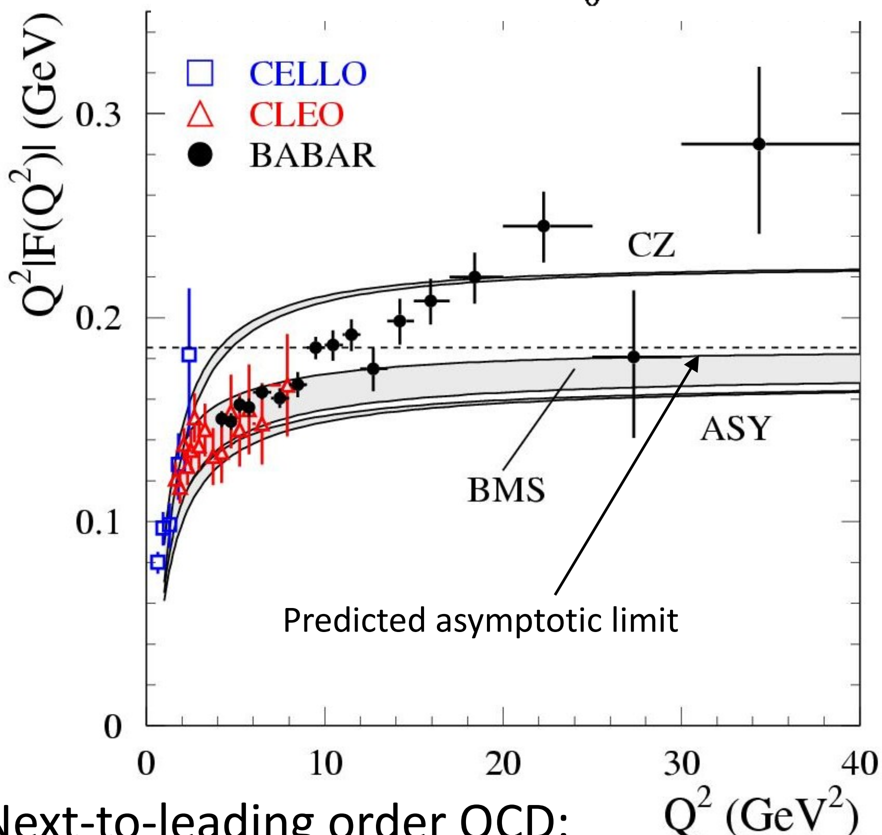
Systematic uncertainty independent of Q^2 is 2.3%.

- **cross section**
- **model uncertainty**

Data: $Q^2|F(Q^2)| \sim Q^{1/2}$
Leading order pQCD: $Q^2|F(Q^2)| \sim$ const.
(in the asymptotic limit)

$e^+e^- \to e^+e^-\pi^0$, Comparison with Theory

$$Q^2F(Q^2) = \frac{\sqrt{2}f_\pi}{3}\int_0^1 \frac{dx}{x}\varphi_\pi(x,Q^2) + O(\alpha_s) + O(\Lambda^2_{QCD}/Q^2)$$



- $Q^2 < 20\ GeV^2$: large difference between the data and the theory in Q^2 dependence . For $Q^2<15\ GeV^2$, none of the models describes the Q^2 dependence well.

- $Q^2 > 20\ GeV^2$: theoretical uncertainties are expected to be smaller. Our data lie above the asymptotic limit at high Q^2, as does the prediction of the CZ model.

Next-to-leading order QCD:

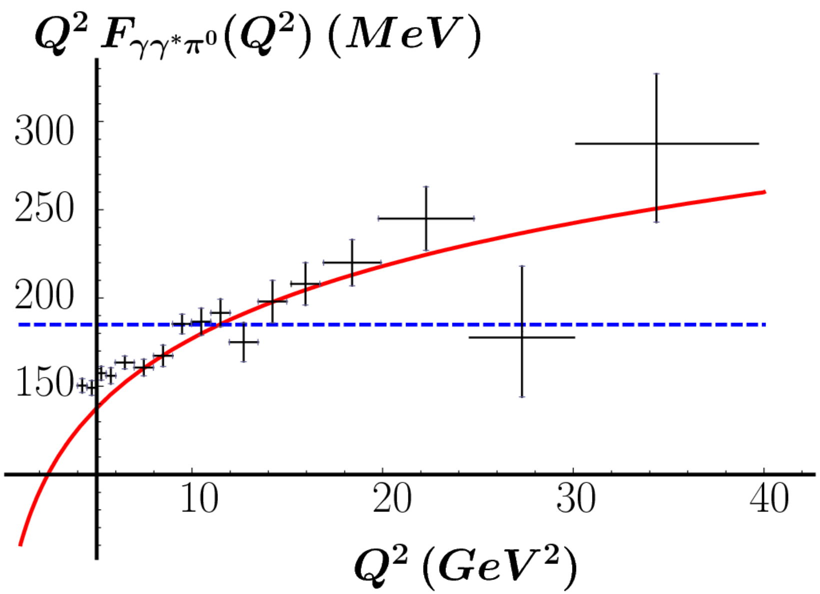
PRD67, 074012 (2003)

- The Chernyak-Zhitnitsky DA (CZ) — Nucl. Phys. B201, 492 (1982)
- The asymptotic DA (ASY) — Phys. Lett. B87, 359 (1979)
- The DA derived from QCD sum rules with non-local condensates (BMS) — Phys. Lett. B508, 279 (2001)

$e^+e^- \to e^+e^-\pi^0$ Calculations, after public release

- The growth of the form factor in $10 < Q^2 < 20$ GeV^2 cannot be explained by NNLO pQCD and power corrections. [S.V. Mikhailov and N.G. Stefanis] Nucl. Phys. B821, 291 (2009)
- A flat pion distribution amplitude is used to reproduce the Q^2 dependence of BaBar data.
  - A.V. Radyushkin — arXiv: 0906.0323
  - M.V. Polyakov — JETP Lett. 90, 228 (2009)
  - H.N. Li and S. Mishima — PRD80, 074024 (2009)

A.V. Radyushkin



H.N. Li and S. Mishima